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# APPLICATION OF A PERFORMANCE COST ESTIMATING RELATIONSHIP TO THE STUDY OF TECHNOLOGICAL CHANGE IN NAVY FIGHTER AIRCRAFT.

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# NAVAL POSTGRADUATE SCHOOL

## Monterey, California

# THESIS

APPLICATION OF A PERFORMANCE COST
ESTIMATING RELATIONSHIP TO THE STUDY OF
TECHNOLOGICAL CHANGE IN NAVY FIGHTER AIRCRAFT

by

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Application of a Performance Cost
Estimating Relationship to the Study of
Technological Change in Navy Fighter Aircraft

by

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## ABSTRACT

The purpose of this study was to develop a performance cost estimating relationship which when used in conjunction with hedonic price index theory, measures technological change in the form of a quality change index. This index was applied to the analysis of price change in Navy fighter aircraft, procured over a period of 1951 to 1961, by adjusting an index of observed price changes to yield a true price index. The resulting analysis showed that if fighter aircraft are purchased for speed and payload, the introduction of new aircraft has enabled the Navy to buy more of these characteristics for any given budget.

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# I. INTRODUCTION

Relying on three basic assumptions: the law of diminishing returns, the Malthusian principle of population, and implicitly, an invariant state of technology, nineteenth century economists made gloomy predictions about future economic growth. History has shown these classical economists to be badly in error. The first half of the twentieth century alone showed a ninety percent increase in productivity that was unexplained by the increase in capital per worker. [Ref. 11] Economists concerned with determining how the classical economists could have erred so badly, have concluded that the error is due to a changing technology.

This increasing awareness in economic thought concerning the importance and implications of technological progress can be dated in 1956 with the appearance of an article by Moses Abramowitz [Ref. 4], and in 1957 with an article by Robert Solow. In attempting to account for the ninety percent increase in productivity, previously mentioned, Abramowitz defined that portion of increased output per man which is left over after increases in capital per man are accounted for, as "the residual," while Solow named it "technological change."

What is technological change and why has technological progress become one of the focal areas of inquiry in economics? Lave [Ref. 11] in his discussion includes, in

addition to Solow's basic definition of "any kind of shift in the production function,"[1] such factors as nonconstant returns to scale, non-neutral technological change, inter-industry shifts of resources, aggregation biases, and several others, as the basis of the phenomenon of technological progress.

According to Brown [Ref. 4], this phenomenon has become one of the focal areas of inquiry for two basic reasons. The first is the inadequately understood and documented problem of structural unemployment related to technological change, and the second relates to recent attention devoted to policies that optimize the returns of available resources. Brown states that "the ruling technology sets the conditions for the optimum use of resources; and similarly, a change in technology alters the optimum use of resources."[2] Brown's statement is ample justification for any study of technological change.

The recent widespread upsurge in environmental awareness and interest in energy conservation is directly related to resource allocation. In microeconomic terms, the opportunity cost of resources, directly affected by changes in technology, is of prime interest to the environmentalist. The importance of technology assessment is amplified by the fact that the

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[1] Solow (1957, p. 312).

[2] Brown (1966, p. 2).

92nd Congress proposed legislature creating an Office of Technology Assessment whose principal assignment would be to contract out studies that would provide Congress with early warnings concerning potential consequences of new technologies and with analysis of alternative measures.

Since optimal use of resources applies to both maximization of output and minimization of cost associated problems, the Department of Defense, and the Navy in particular, have become increasingly aware of the problems associated with a changing technology and its effect on resource allocation. This study addresses this problem by attempting to measure the change in cost of performance characteristics as related to the change in cost of fighter aircraft.

This study is an attempt to apply the theory of hedonic price indices to the analysis of price change in Navy fighter aircraft. The theory requires the incorporation of technological change into a quality change index. This index can be used to answer questions such as what the price of a combination of performance characteristics of a particular fighter aircraft would be in a period in which that particular combination was not produced. A better understanding of the effects of technological change in this model should be of benefit to the Navy in dealing with the problems discussed in the preceding paragraph.

The plan of the paper is to first investigate the historical background of technological change and the trends established by these initial efforts, then select the proposed

alternative method of accounting for technological change to be associated with hedonic price index theory, and develop the theory on which it is based. This model is then applied to the aircraft problem previously mentioned. The method selected requires the development of various cost estimating relationships to be used in the quality change index. The development and documentation of the cost estimating relationships and the alternative uses of the results, are discussed in the next sections. Summary and conclusions are presented in the final section.

## II. HISTORICAL BACKGROUND

Although the need to explain productivity growth resulted in the study of technological change, the phenomenon is not limited to situations which involve input-output relationships of the productivity type. Nevertheless, initial efforts were directed towards developing productivity models. A better understanding of the concept of technological change can be obtained by examining a few of these historical models.

In these models, the primary tool used to measure technological change is the production function, since it is a technical relation describing how an input combination results in a maximum numerical output. Often, in order that the production function adequately describes or represents the economic situation being investigated, several constraining assumptions will have to be made. These important assumptions will be included in the discussion of the basic models along with the problems which limit the models usefulness in explaining technological progress.

The concept of the total or multifactor productivity index combined with appropriate production function assumptions forms the basis for the first two models to be discussed. Total factor productivity, the ratio of output per unit of labor and capital combined, is also referred to as the "residual or index of technical progress." [Ref. 13] The index takes the form $A = Q/(\alpha L + \beta K)$, where Q, L, and K

represent, respectively, output, labor, and capital, with $\alpha$ and $\beta$ being appropriate weights.

By implicitly assuming a homogeneous production function and the Euler condition, J. Kendrick obtains the following as his arithmetic index:

$$dA/A = [(Q_1/Q_0)/(wL_1 + rK_1)/(wL_0 + rK_0)] - 1$$

> "The weights in this measure are changing over time and the aggregate production function consistent with this index is $Q = tKL/(CL^\rho + dK^\rho)^{1/\rho}$ which is a linear homogeneous production function with constant elasticity of substitution, $\sigma = 1/(1+\rho)$, c and d are the efficiency parameters, $\rho$ is the elasticity parameter, and t is the disembodied neutral technical change."[3]

Thus, the assumption that is critical here is that capital and labor increase in approximately the same proportion and that wage rate, w, and the rate of return on capital, r, are affected only by technological change. Kendrick's model runs into difficulty when applied over a long period of time because the measure of technological change, which is a measure of the amount the appropriate isoquant is shifted out along a ray from the origin, becomes difficult to interpret. This results, in part, from the fact that associated with a change in prices, is a sideward movement along the isoquant. The confusion cannot be resolved by the choice of either current or constant prices because there is no evidence that one set of prices is preferable to another [Ref. 11].

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[3]Nadiri (1970, p. 1138).

Robert Solow first used the term "technological change" when he developed his index, which with slight modification is a geometric index, in 1957. Much of the criticism directed at Solow's model is due to the very general assumptions he made in the development of the model. In addition to the assumption of an aggregate production function, of the form $Q = A(t)f(K,L)$, that exhibits constant returns to scale and is homogeneous, Solow assumed perfect competition and neutral technological change. The technological change between two periods is given by the equation $dA/A = dQ/Q - [\alpha^{dL}/L + \beta^{dK}/K]$, where $\alpha$ and $\beta$ are the elasticities of output with respect to capital and labor. Interpretation of the model implies that whatever part of output is not explained by increases in capital and labor must be assigned to technological change. This model differs from the arithmetic index in that weighting is by the elasticity of output with respect to each factor rather than by prices. Solow's model is also questionable over long periods of time primarily due to the assumption of neutral technological change and the numerous problems associated with an aggregate production function.

One of the hardest worked aggregate production functions is the linear in logs, or generalized Cobb-Douglas form. Extensive use of this functional form has been directed towards decomposing the Abramowitz "residual" into components such as neutral and non-neutral technological progress, and economies and dis-economies of scale. Initial use of

Cobb-Douglas models was restricted to the study of neutral technological change. It has since been generalized to permit quantification of returns to scale and to account for non-neutral as well as neutral technological change. [Ref. 4]

The general form of the equation, $Q = AL^{\alpha}K^{\beta}$, makes the shares of labor and capital in income, $\alpha$ and $\beta$, as well as output, technological change, labor and capital, Q, A, L, K, functions of time. The Cobb-Douglas function can be expanded to include an efficiency component, specified by an exponential $e^{\gamma t}$, thus forming a production function, $Q = AL^{\alpha}K^{\beta}e^{\gamma t}$, which when converted to logarithms and fitted to time series data yields an estimate of the productivity advance coefficient $\gamma$, and the elasticities of production with respect to labor and capital. [Ref. 4]

In addition to assuming neutral technological change, a necessary assumption, this model is greatly affected by the number and classification of variables. [Ref. 16] Any errors due to the misspecification of the form of the function will be incorporated in the measure of technical change.

Despite the extensive use of the Cobb-Douglas production function as a tool for measuring technological progress, the assumption of unitary elasticity of substitution, and its difficulty in accounting for non-neutral technological change, have rendered it suspect. The constant elasticity of substitution (CES) production function, derived by Arrow, Chenery, Minhas, and Solow, allows the elasticity of

substitution to be estimated. Because this function contains both efficiency and distribution parameters, and permits the representation of returns to scale in a parameter or set of parameters spearately from other parameters, it can be used to estimate both neutral and non-neutral technological change.

Utilizing variables for output, capital and labor, as defined previously, and measuring these variables in index number terms with a common base period, the CES production function takes the form $Q = \gamma[\delta K^{-\rho} + (1-\delta)L^{-\rho}]^{-\mu/\rho}$ . Parameters $\gamma$, $\delta$, $\rho$, $\mu$, are, respectively, the parameters of efficiency, distribution, substitution, and degrees of returns to scale, where the elasticity of substitution of labor for capital $\sigma = 1/(1+\rho)$. [Ref. 13]

Since for the Cobb-Douglas production function, $\sigma = 1$, and for the Leontief, $\sigma = 0$, the CES function obviously includes these functions as special cases. Despite its shortcomings, the CES function has proved valuable and applicable to several important economic problems.

The models discussed to this point are well established, often utilized, models which have been subjected to considerable scrutiny over time. Each has been found wanting in one or more areas for a variety of reasons both extensive and diverse. Recognizing the degree of bias, introduced into the measure of technological change, associated with these problems, economists have recently devoted considerable effort towards developing models which remove these biases

thereby providing a "true" measure of technical change in the economy. The reader is referred to Nadiri's survey for a brief summary of the direction several economists have taken towards more accurate measurement of total factor productivity. Some have tended towards development of new functional forms, many of which amend and, or, expand upon the models previously discussed. Others have tended towards better understanding and more accurate use of the models already available.

Since the study of technological change resulted from the need to explain productivity growth, unaccounted for by classical economic theory, Griliches [Ref. 6] felt that theories incorporating unstable production functions were, towards this end, unsatisfactory. Large unexplained shifts in production functions are not very helpful in understanding growth. Furthermore, the trend in economic research towards more accurate measurement of technical change is of questionable benefit if the change itself is not understood and, or, well defined.

The problem is to develop a model utilizing a stable production function in which all increases in output can be attributed to increases in some factor. The Griliches model, in which the production function remains constant over long periods of time, measures changes in output in terms of changes in quantities and qualities of inputs and economies of scale. It is, by no means, an attempt to remove technical change from the explanation of growth; instead it is designed

to separate the "residual" into movements along a more general production function and into identifiable changes in the qualities of inputs. Further, it is possible to adjust the independent variable for quality change.

The basic concept of the Griliches model is to estimate a general aggregate production function for a particular segment of the economy at one period in time, substitute in the values of the appropriate parameters at some later period in time, then measure the increase in output attributable to each factor and to technological change.

The advantage of the model is that it deals with the problem explicitly. It does, however, require considerable estimation, and is thus subject to the usual econometric problems, as well as to the problems associated with a somewhat unrealistic aggregate production function.

Griliches' work will provide the methods needed to move away from the strict production function relationship of output to a combination of inputs. Adaptation of his models and application of some price index theory make possible study of technological change in a cost analysis form.

## III. PROBLEM DEVELOPMENT

The transition from the pure theory and measurement of total factor productivity to an econometric analysis of quality change is made by utilizing the methods associated with the theory of hedonic price indexes. The first task is to find what relationship, if any, exists between the price of a particular commodity and its quality. The approach taken in this paper is based on work done previously by Griliches. Griliches noted that a variety of models of a particular commodity, with different specifications can be observed being sold at different prices during the same time period. This data can then be used to derive implicit prices per additional unit of the chosen dimension of the commodity. An adjustment in price is then made to account for the changes in the specifications of the commodity. In general, the main idea is, according to Griliches: "Derive implicit specification prices from cross-sectional data on the price of various "models" of the particular item and use these in pricing the time series change in specifications of the chosen (average or representative) item."[4]

In order to develop a relationship between quality change and change in output price, it is necessary to break away from the traditional association of output price changes with

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[4]Griliches (1968, p. 104).

changes in input cost, and establish, instead, a connection with changes in properties, dimensions, or other particular characteristics. The first step in this process is to develop an appropriate functional relationship.

Since many commodities are sold in a number of different models, it is possible to observe, in a designated time period, a population of prices for the different models of a particular commodity. The different prices are the result of differences in properties, dimensions, or other characteristics of the various models. Grouping these properties under the general heading of qualities, each individual price can be written as a function of a set of qualities. The resulting equation takes the form:

$$p_{it} = f_t(x_{1it}, x_{2it}, \ldots, x_{kit}, u_{it}) ,$$

where $p_{it}$ is the price of the $i^{th}$ model of a commodity in time period of observation t, $x_{kit}$ is the measure of the $k^{th}$ quality of model i in time period t, and $u_{it}$ is the disturbance.

There is no a priori reason to expect price and quality to be related in any fixed quantitative fashion. Griliches, in his study of the automobile industry, used the semilogarithmic form. The empirical development of the functional relationship to be used in this study is treated as a problem in parametric cost estimation. Discussion of the solution to this problem is presented in a later section. What follows here is a discussion of some of the more general problems,

and their solutions, which may be encountered in developing the relationships which make up a quality change index.

It may be the case that the measurement of particular important qualities is not possible. In this case "proxy" variables, which are well correlated to the qualities desired though not in themselves desirable, may be used to approximate the more desirable variables.

If a particular quality cannot be quantified numerically, "dummy" variables can be used to measure the average contribution of the quality, to the price of the item, by assigning the value of one if the item possesses the particular quality and zero if it does not. This technique will only be successful if a sufficient number of observations are available.

If, after making the necessary assumptions about the number and kind of relevant qualities and fixing the form in which they affect price, a sufficiently precise equation results, then it can be used to estimate the value of quality changes in a chosen base period. Additionally, it can be used to estimate the price of a new set of qualities which were not available in the base period, provided that the new set differs only quantitatively in its qualities from the previously available set, and does not contain some new, altogether different qualities.

When using these equations to compare different time periods, the resulting implicit prices will depend on the particular period chosen as the base period. Laspeyre's and Paasche's indexes might differ significantly. Griliches

presents a technique, first developed by A. T. Court in his paper "Hedonic Price Indexes with Automotive Examples," in The Dynamics of Automotive Demand, New York, 1939, which can be used to estimate the average price change directly by assuming the equation holds well enough in both time periods except for the additional variable, time. The procedure is to add a "dummy" variable to each equation that is zero in the first period and one in the second. The coefficient of this variable, holding the change in any of the measured qualities constant, provides an estimate of the average percentage increase in model price between the two periods. Utilizing these various techniques, a quality change index can now be developed.

These equations are used to define an index of quality changes as follows: Let

$P_{it} = f_t(x_{1it}, \ldots, x_{kit}, D_{1it}, \ldots, D_{mit}, u_{it})$

i = model i of a particular commodity $i=1, \ldots, r$

t = time period of observation, 0 = base period

$X_{kit}$ = characteristic k of model i in time period t

$D_{mit}$ = dummy variable m for model i in time period t

$u_{it}$ = disturbance;

and form the following regression equation:

$$\hat{P}_t = \alpha_0 + \alpha_1 X_{1t} + \ldots + \alpha_k X_{kt} + \alpha_{k+1} D_{1t} + \ldots + \alpha_n D_{mt} + u_t$$

then define the quality change index as:

$$q_i = \hat{P}_{it}/\hat{P}_{i0}$$

where $\hat{P}_{it}$ = the predicted value for model i on the basis of estimated equation $f_t$ for the combination of characteristics model i has in period t, and $\hat{P}_{i0}$ = the predicted value for model i based on estimated equation $f_t$ using a set of characteristics for base period 0. This quality change index measures, for a particular model, the percentage change in price predicted by the function $f_t$ on the basis of the change in the level of the different qualities between the two periods. For a large number of models, these ratios can be aggregated into a quality change index, using the same weights that would be used in aggregating their prices into a particular price index.

Now that the quality change index has been developed, in theory, it must be put to proper use. The objective is to obtain adjusted real change in price. Price indexes, unadjusted for quality change, for the commodity being studied, are either derived, if necessary, or provided by the Bureau of Labor Statistics, depending on the commodity, if available. The ratio of this price index over the quality change index, is the true price index.

With this basic understanding of the theory associated with the problem of measuring quality change, the solution method can now be developed.

## IV. DEVELOPMENT OF THE COST ESTIMATING RELATIONSHIP

The development of estimating relationships is made less complicated by following a set of general procedural steps. This type of logical progression is presented in Kluge's paper [Ref. 9]. This section presents the general development of the cost estimating relationships which form the quality change index. The following sections present the numerical development, evaluation, and documentation of these relationships.

It was stated earlier that the empirical development of the quality change index can be treated as a problem in parametric cost estimation. This is only partially true. Parametric cost analysis can be described as a process involving development and application of cost estimating relationships (CERs). The regression equations developed for use in a quality change index are of the same form as cost estimating relationships, but their application is somewhat different. The quality change index regression equations are estimating relationships in that they are statements of how one or more technically descriptive parameters affect cost, but they are used for explanatory, rather than predictive purposes. The parametric cost estimating relationship is applied by substituting parameter values into a derived regression equation, calculating a cost, and assigning that cost to the item. A prediction interval is

is then calculated which puts a boundary around the predicted value of the dependent variable. As a result, a statement can be made, with a certain level of confidence, that the predicted value will be in this interval. Nevertheless, since the form of the quality change index regression equations are the same as estimating relationships, the general procedureal development will be the same. Therefore, this section proceeds with the development of the cost estimating relationships to be used in the quality change index.

The general procedural development of the relationship follows a logical sequence of steps. The initial step in this procedural development is problem definition. This in itself is a many sided problem. The analyst must become familiar with the environment in which he is working. More specifically, he must acquire an understanding of the background of the problem he intends to solve. This will enable him to establish the current state of the art, and how this has changed over any time period in which he might be interested. He must determine the characteristics and associated parameters of the system for which the estimating equations are being developed. Additionally, he should get an idea of a range of values for these parameters. With this information in hand, the analyst should have an adequate feel for the complexity of the problem.

The problem addressed in this paper is to develop an estimating equation for United States Navy fighter aircraft

flyaway cost. The time frame is, generally, 1950 through 1970. Background information was obtained primarily from technical publications dealing with this subject, but also from experience as a designated naval flight officer, and from consultation with other experienced aviators.

The descriptive parameters can be categorized into two basic groups. The first is the group of physical characteristics which describe the aircraft. Examples of this type include takeoff gross weight, engine thrust, physical dimensions, fuel capacity, and many others. These parameters are very specific, well defined, and easily quantifiable. This cannot be said, in general, of the second group which contains the performance characteristics of the aircraft. Variables such as maximum airspeed, combat range, and ordnance payload, which describe aircraft capabilities, are highly dependent on such factors as weather, aircraft configuration, and type of mission. The two categories together provide a very complete description of the aircraft weapons system.

With the problem defined, and its objectives understood, the analyst must now select an approach and acquire necessary data. Developing estimating relationships requires consideration of an important question regarding emphasis on data versus theory. One approach tends to emphasize the importance of good data and the use of formal statistical methods, the other the importance of explanatory theory and careful

choice of functional expressions. Ideally, the analyst draws upon the best from both methods.

Along with selecting an approach, the analyst must choose which variables will be possible candidates for use in his equations. The important consideration is that the variables relate to the entire study effort. The analyst's choice of variables is based on judgement and logic resulting from his background research and problem familiarization. If the relationship being developed is to be used for sensitivity analysis, the analyst must be aware of the potential multicolinearity problem.

It is possible that the analyst might not be faced with the variable selection problem. In some cases, fully documented general relationships may have been previously developed. Examples of some general relationships for aircraft systems can be found in Alexander [Ref. 1], Large [Ref. 10], [Ref. 12], and Scott [Ref. 14]. Considerable data for this paper was taken from Scott's study of a parametric estimate of aircraft flyaway cost. If expediency is a requirement, use of a general relationship may be necessary; however, the results will normally be inferior in quality to those obtained from a problem-specific relationship.

The approach taken in this paper is very much problem-specific. The quality change index is composed of equations which relate aircraft cost to specific performance characteristics. Scott's relationship [Ref. 14] which predicts

flyaway cost as a function of take off gross weight and several variables related to the quantity of each aircraft model purchased, as well as a model using strictly physical characteristic type variables, were rejected for use in this study because it is felt that the Department of Defense, in its procurement decisions, is interested not in weight and thrust, but instead in performance capabilities. The variables selected for this study represent mission speed, mission payload, and a complicated measure of mission capability, none of which can be quantified without much more specific definitions.

In order to ensure uniformity of measurement over all fighter aircraft models considered, the following initial conditions and basic definitions are established for each model.

MISSION: General purpose fighter...This requires a carrier based aircraft whose primary mission is destruction of enemy aircraft.

WEATHER CONDITIONS: Standard day...This implies that the temperature equals fifteen degrees centigrade and the atmospheric pressure equals 29.92 inches of mercury at sea level.

MISSION PAYLOAD: Configuration...This implies that the aircraft carries the maximum appropriate ordnance when configured for the general purpose fighter mission.

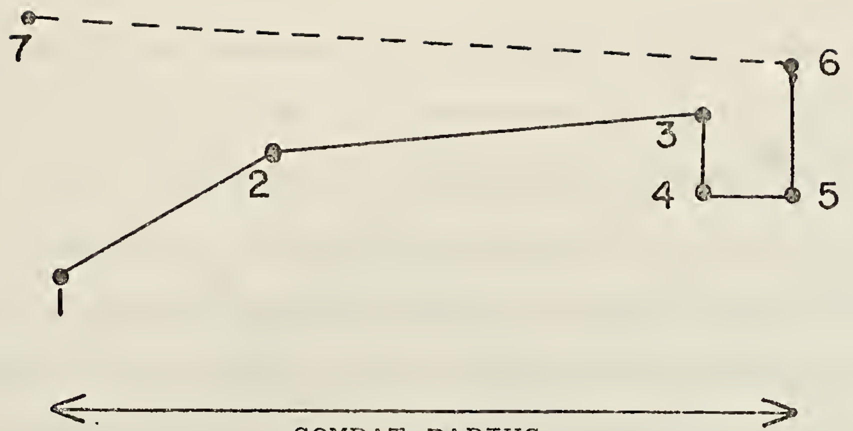
MISSION SPEED: This is a measure of the maximum knots obtainable at thirty five thousand feet on a standard day with the configuration and mission of a general purpose fighter.

MISSION TIME: Mission capability...The data for this variable is an output from the general purpose fighter combat problem outlined in Figure One.

The quality change index is composed of problem-specific regression equations relating aircraft flyaway cost to performance characteristics constrained by the conditions established above. Consideration should now be given to the appropriate functional form.

The discussion presented in Section II of this paper is a good indicator of the difficulty involved in selecting an appropriate functional form. Although the decision in the development of a quality change index does not involve a choice among different forms of production functions, many of the problems to be considered are similar. A primary consideration should be the establishment of a causal relationship based on a logical correlation between cost and the descriptive parameters, as well as on the statistical properties of the relationship.

One question which must be answered is whether or not to disaggregate. In the aircraft industry, this involves dividing the aircraft weapons system into engine, airframe, and avionics subsystems. This technique is often attractive when the analyst is confronted with a small number of data




1..2..3..4 = Outbound leg

4..5..6 = Combat

6..7 = Inbound leg

1.. Warm up, taxi, takeoff: Requires five minutes at normal thrust.

1..2 Climb: Climb to cruising ceiling at military power.

2..3 Cruise out: Fly at maximum range velocity at the cruising ceiling.

3..4 Descend: Descend to 35,000 feet (Requires no time or fuel).

4..5..6 Combat: Fly at military power at 35,000 feet for twenty minutes. Comclude combat at initial cruise back altitude.

6..7 Cruise back: Fly at maximum range velocity at the cruising ceiling

7.. Reserve: Fly for twenty minutes at the velocity for maximum endurance at sea level plus five percent of initial fuel load.

MISSION TIME includes time for climb plus time for cruise out plus time for combat and cruise back.

FIGURE 1.

points. The likelihood of identifying and describing causal relationships may improve with disaggregation because only a major subsystem and not the whole equipment is addressed at any one time. Examples of relationships developed for the aircraft industry, using this technique, can be found in "Methods of Estimating Fixed-Wing Airframe Costs," [Ref. 12] and Large, J. P., [Ref. 10]. Statistical questions concerning the bias of the estimates and the effect of combining the variations in the cost estimating relationships result from the use of this technique.

Disaggregation was rejected for use in this paper because the relationship established involves performance characteristics of the aircraft as a whole; therefore, dividing the weapons system into subsystems would not be appropriate.

The final decision of the analyst, the functional form of his relationship, is critical because not only must the relationship be applicable, it must also be creditable. This can be a problem when deciding whether to use linear, semi-logarithmic, logarithmic, or polynomial forms. For this decision, expectation of better statistical results is not, in itself, a sufficient justification for the choice of a particular form.

In his study of the automobile industry, Griliches uses the semi-logarithmic form because, "if natural logarithms are used, an 'a' coefficient (the estimated coefficient) will provide an estimate of the percentage increase in

price due to a one unit change in the particular quality, holding the level of the other qualities constant."[5] Griliches' choice of the semi-logarithmic form is based entirely on ease of interpretation and not necessarily on a causal relationship type argument.

There appears to be justification in this study for evaluation of the logarithmic form; as a logarithmic or polynomial form often appears in performance cost estimating relationships with the explanation that with fixed technology, marginal costs of performance should be increasing. The question remains as to whether or not a logarithmic transformation would be advantageous. Since initial calculations using the linear form resulted in a negative intercept, and because the use of a logarithmic form, in this type problem, is justified, a logarithmic transformation was evaluated to determine if it might provide a more applicable form. The results (Appendix A) were rejected because they provided no significant statistical advantage, and the large exponential coefficient in the 1951-1954 model appeared unreasonable. The statistical rejection of the logarithmic form here may be due to scarcity of data or perhaps to the fact that each regression was done for a narrow time span, therefore limiting the range of characteristics to those where technology was not pushed into "high" cost areas.

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[5] Griliches (1968, p. 106).

When the analyst has established that the relationship he has developed is both applicable and creditable, he must collect the necessary input information. One of the most important, often time consuming and expensive, steps necessary in the development of a cost model, is the collection and refinement of data.

Morris Zusman, however, states "that the cost analyst rapidly runs into the law of diminishing returns for effort expended gathering additonal data and/or refining data in his possession when his productivity is measured as the reduction in the confidence bandwidth about the cost estimate."[6] He argues that the uncertainty about an estimate is caused by essentially three factors, the randomness of the actual cost distribution, the randomness of the cost estimator's distribution, and the bias of the estimator. For most practical problems only the estimator's variance can be reduced by increasing the data base size and refining data. The cost randomness and estimator bias are essentially independent of the data base size and degree of refinement [Ref. 18]. The argument is then that the temptation to increase sample size in order to gain statistical confidence must be overcome as it can amplify the previously mentioned problems associated with data collection. The analyst should consider this argument, but he must also remember that as the sample size becomes large, the estimated variance becomes

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[6]Zusman (1969, p. IV).

smaller and approaches the true variance. In general, the amount of effort that can be expended on this problem will be somewhat determined by the particular study and the amount of money and time available.

If the analyst has done his background research well the problem of collecting both parametric and cost data should be easier. Two good references for the steps to follow in the collection process are Batchelder [Ref. 3], and Kluge [Ref. 9].

For this study, the cost data were obtained form the Naval Air Systems Command "PAMN Budget Back-up Book," which details the cost elements of the PAMN appropriation category. They are in current dollars for budget estimates. For example, typical cost data on a FY 1969 aircraft purchase contract are based on an estimate made in August 1969 (after the end of FY 1969) for the FY 1971 budget decision regarding procurement of this particular aircraft model. Cost data used in the estimating relationship developed for this paper are flyaway costs. Flyaway cost is the cost of procuring an aircraft ready to fly an operational mission. It does not include any research and development, logistic support, or operating costs. The total program cost is the sum of research and development and investment costs. Flyaway cost is one element of investment cost which also includes the cost of initial spares and support equipment.

The parametric data was extracted from the Naval Air Systems Command <u>Standard Aircraft Characteristics</u> manual,

for each model. Data is available from this source for a wide range of both physical and performance characteristics. A matrix of data used in developing the cost estimation relationship for this study is presented in Appendix B.

Table One is a list of the fighter aircraft models used in this study. Included in Table One is the ordnance configuration of each aircraft model. The fighter models used in this study were limited by data availability. An attempt was made to use every model for which a complete set of data was available.

The next steps in the general development of a cost estimating relationship are to normalize the data and, if necessary, adjust the approach. Cost data adjustments may be necessary due to learning curve effects, inflation effects, and inconsistencies due to contractor cost definitions. One such adjustment considered in this study was to figure costs in 1971 dollars using an index, derived by Naval Air Systems Command, shown in Table Two. Although this adjustment was rejected because the nature of the study required investigation of cost changes over a period of time, the table is presented for possible use in future research in this area. No adjustments were made for learning curve effects since it was desired to have the cost figures used in this study reflect the effect of past decisions; however, this too could be a subject for future research. Considerable effort was devoted to the collection of a consistent set of both cost and parametric data. The independent variables in the

TABLE ONE

FIGHTER MODELS AND ORDNANCE CONFIGURATION

| | |
|---|---|
| F9F5 | Internal guns and ammunition |
| F9F6 | Internal guns and ammunition |
| F9F7 | Internal guns and ammunition |
| F9F8 | Four sidewinder missiles |
| F3H2N | Internal guns/ammunition and four sparrow missiles |
| F4D1 | Four sidewinder missiles |
| FJ4 | Four sidewinder missiles |
| FJ4B | Four sidewinder missiles |
| F11F1 | Four sidewinder missiles |
| F9F8 | Four sidewinder missiles |
| F3H2 | Four sparrow missiles |
| F8U1 | Two sidewinder missiles and 32 2.75 rockets |
| F8U2 | Thirty-two 2.75 rockets |
| F8U2N/2NE* | Four sidewinder missiles |
| F4A/B* | Four sparrow missiles |

* The data for these models are combined.

TABLE TWO

AIRCRAFT PROCUREMENT COST INDEX

Source: NAVAIR 501

| Year | Index |
|---|---|
| 1950 | .437 |
| 1951 | .455 |
| 1952 | .474 |
| 1953 | .490 |
| 1954 | .508 |
| 1955 | .532 |
| 1956 | .571 |
| 1957 | .599 |
| 1958 | .613 |
| 1959 | .633 |
| 1960 | .649 |
| 1961 | .671 |
| 1962 | .685 |
| 1963 | .719 |
| 1964 | .730 |
| 1965 | .752 |
| 1966 | .787 |
| 1967 | .826 |
| 1968 | .870 |
| 1969 | .917 |
| 1970 | .962 |
| 1971 | 1.000 |

cost estimating relationship have been carefully defined so that the parametric data requires very little, if any, adjustment.

With data in hand, the analyst is now ready to proceed from theoretical to mathematical relationships. The model is exercised and then evaluated by determining how well it explains the data with which it was exercised, and to what degree it solves the problem being studied.

The process of evaluating the data by exercising the model is usually iterative in nature. At each step changes, usually minor but occasionally major, are made in the model until, in its final form, the analyst is satisfied with the model. This process was used in solving the problem addressed in this paper.

As previously stated, the cost estimating relationship developed in this study is a linear regression model. Both stepwise and multiple linear regression, utilizing the Biomedical 02R and 03R programs [Ref. 5], were used to evaluate cost as the dependent variable versus mission speed, mission payload, and mission time as independent variables. Thirty-two cases were evaluated for seventeen models over a time span of 1951 through 1959. The model at this point was:

$$\hat{P} = a_0 + a_1 \begin{bmatrix} \text{Mission} \\ \text{Speed} \end{bmatrix} + a_2 \begin{bmatrix} \text{Mission} \\ \text{Payload} \end{bmatrix} + a_3 \begin{bmatrix} \text{Mission} \\ \text{Time} \end{bmatrix} + u$$

where $\hat{P}$ = flyaway cost as previously defined. This model was rejected because statistical results (Appendix A) indicated that the contribution of mission time to the explanation of cost and reduction of variance was not sufficient to warrant its inclusion in the model. Additionally, it was decided not to include repeated cases of the same aircraft model, with identical performance characteristics, where only the cost changed, as time changed. This decision was made because the estimating relationship is being developed to be used primarily in the measurement of technological change associated with design changes and the resulting effect on aircraft performance, not in the measurement of changes in contract cost. Including the same aircraft more than once in the same model could introduce an undesirable bias.

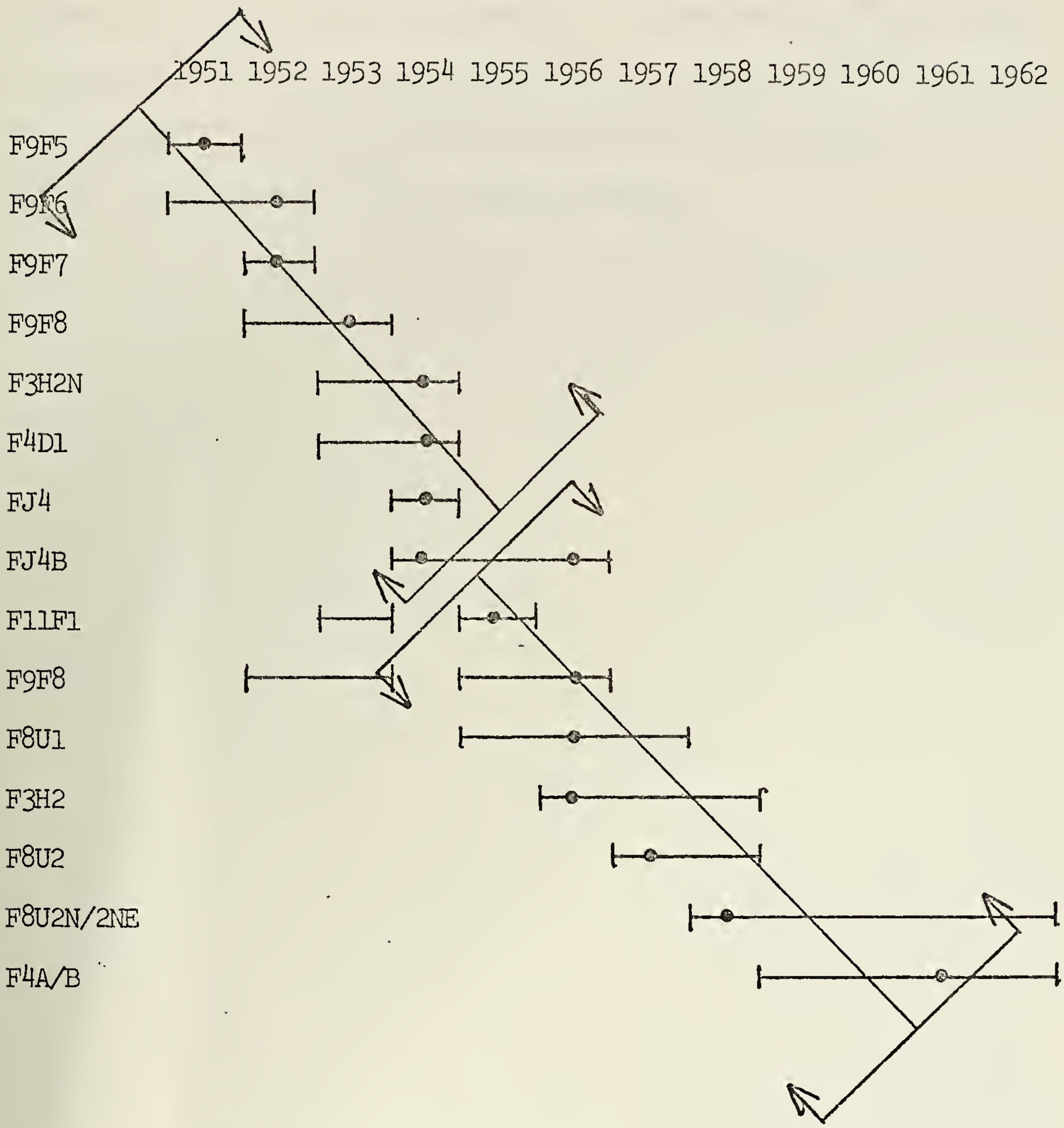
Plotting time lines of the individual models (Figure Two) provided insight which was used to divide the models into two distinct groups. The first group included eight models and covered a time span of 1951 through 1954, while the second group also included eight models and covered a time span of 1955 through 1961.

As a result of these initial efforts, it was determined that the cost estimating relationship which should be fully developed was one of the form:

$$\hat{P} = \alpha_0 + \alpha_1 X_1 + \alpha_2 X_2 + u$$

FIGURE 2

TIME LINE FOR FIGHTER
MODELS STUDIED



where $\hat{P}$ = predicted flyaway cost, $X_1$ = maximum speed at thirty five thousand feet on a standard day, $X_2$ = maximum ordnance payload for a general purpose fighter aircraft mission, and u = the disturbance. A separate relationship is developed for each of the two time spans. The numerical development, evaluation and documentation of these relationships is presented in the next section.

## V. EVALUATION OF THE COST ESTIMATING RELATIONSHIP

Simple least-squares estimation methods are used in this paper to estimate the coefficients of the independent variables in the general regression equation,

$$P_i = a_0 + a_1X_{1i} + a_2X_{2i} + u_i$$

describing the relationship of the dependent variable, flyaway cost, to the independent variables, mission speed and mission payload. The actual equations describing the relationship are:

For the period 1951-1954,

$$\hat{P}_i = -2.746 + 0.531\ X_{1i} + 0.081\ X_{2i} + u_i$$

and for the period 1955-1961,

$$\hat{P}_i = -1.134 + 0.226\ X_{1i} + 0.047\ X_{2i} + u_i$$

where $\hat{P}_i$ = predicted flyaway cost for model i, $X_{1i}$ = mission speed for model i, $X_{2i}$ = mission payload for model i, $u_i$ = the distrubance or stochastic error terms for each model, and i = 1,...,8 observations for each time period.

The assumptions made in evaluating these relationships are that the disturbances are normally distributed, with expected value equal to zero, and constant variance. The chi-square test to determine the validity of these assumptions was not evaluated due to the very small sample size. As an alternative, the residual plots were investigated. Their

randomness indicated that the assumptions could be accepted as valid. Subsequent evaluation of the statistical properties of the estimated coefficients is dependent upon the acceptance of these assumptions. Under these assumptions, the method of least-squares produces unbiased maximum likelihood estimators.

The statistical evaluation of a cost estimating relatinship, designed to determine how well the estimating equation describes the sample observations, is dependent upon the values of the standard error of the estimate, SE, the standard error of the coefficient of each independent variable, $S_{a1}$ and $S_{a2}$, the coefficient of variation, CV, and the coefficient of determination, $R^2$. Additionally, the hypotheses that each independent variable has no statistical influence on the dependent variable, and that the equation as a whole has no statistical influence, must be tested and either accepted or rejected.

All subsequent statements about the statistical evaluation of the cost estimating relationships developed in this paper are based on the summary of statistics presented in Table Three. The value of the SE, which measures the magnitude of the variance unexplained by the regression equation, is acceptable. Values as small as 0.1 to 0.2 are desirable for the coefficient of variation, however, a value of 0.26 is not unreasonably large. The coefficient of determination is a measure of the proportion of total variance accounted for by the estimating relationship. The values of $0.90^+$ are

# TABLE THREE

## SUMMARY OF STATISTICS

**Time Period 1951-1954 Model**

$P = -2.746+0.531X_1+0.081X_2+u$

$X_1$ = Mission Speed

$X_2$ = Mission Payload

$R^2 = 0.9038$

$SE = 0.1744$

$CV = 0.262$

$F = 22.4808$

$\bar{P} = 0.666$

| $X_1$ Statistics | $X_2$ Statistics |
|---|---|
| $S_{a1} = 0.18726$ | $S_{a2} = 0.01499$ |
| "$t_1$" = 2.83586 | "$t_2$" = 5.38235 |
| $\bar{X}_1 = 5.107$ | $\bar{X}_2 = 8.675$ |

Correlation Coefficients

| | Flyaway Cost | Mission Speed | Mission Payload |
|---|---|---|---|
| Flyaway Cost | 1.0000 | 0.2385 | 0.5884 |
| Mission Speed | | 1.0000 | 0.8655 |
| Mission Payload | | | 1.0000 |

**Time Period 1955-1961 Model**

$P = -1.134+0.226X_1+0.047X_2+u$

$X_1$ = Mission Speed

$X_2$ = Mission Payload

$R^2 = 0.9014$

$SE = 0.2667$

$CV = 0.263$

$F = 22.8039$

$\bar{P} = 1.105$

| $X_1$ Statistics | $X_2$ Statistics |
|---|---|
| $S_{a1} = 0.03610$ | $S_{a2} = 0.02734$ |
| "$t_1$" = 6.25875 | "$t_2$" = 1.36050 |
| $\bar{X}_1 = 7.906$ | $\bar{X}_2 = 12.175$ |

Correlation Coefficients

| | Flyaway Cost | Mission Speed | Mission Payload |
|---|---|---|---|
| Flyaway Cost | 1.0000 | 0.1847 | 0.9300 |
| Mission Speed | | 1.0000 | 0.3595 |
| Mission Payload | | | 1.0000 |

acceptable in this study. The "t" statistics allow the analyst to make the statement that, with one exception, at the 95% confidence level, there is only 5% chance on the average that one will conclude that the coefficients of the independent variables are significantly different from zero when in fact they are not. This statement can only be made with 80% confidence with respect to the coefficient for mission payload for the later time period. It is felt that this is partially explained by the fact that it was more difficult to determine the appropriate mission payload for the more recent aircraft models, which have increasingly more sophisticated weapons systems. Based on the F values, the hypothesis that the equation as a whole has no statistical significance, can be rejected, for both time periods, with 99% confidence. Finally, as indicated by the correlation coefficient matrices, there may be a correlation problem between speed and payload in the 1951-1954 model. However, this correlation is very non-intuitive and does not appear in the 1955-1961 model. Furthermore, the "t" statistics for both coefficients in the 1951-1954 model are excellent and the ratio of coefficients between models is stable. For these reasons, the possibility of unacceptable multicollinearity seems slight. Appendix D contains a collection of appropriate graphs and scatter plots.

One important observation, not directly related to statistical analysis, can be made in regards to a comparison of the coefficients of the relationships for the time periods.

This observation is that the marginal costs of one unit of both mission speed and mission payload have decreased in the later time period model. Additionally, investigation of average costs shows somewhat similar results. Development of this average cost relationship requires use of the following numbers:

| Time Period 1951-1954 | | Time Period 1955-1961 | |
|---|---|---|---|
| Mean value of cost | = 0.666 | Mean value of cost | = 1.105 |
| Mean value of speed | = 5.107 | Mean value of speed | = 7.906 |
| Mean value of payload | = 8.675 | Mean value of payload | =12.175 |
| Average cost per knot (carrying 8.67 pounds) | = 0.127 | Average cost per knot (carrying 12.17 pounds) | = 0.136 |
| Average cost per pound (flying 5.110 knots) | = 0.075 | Average cost per pound (flying 7.910 knots) | = 0.088 |
| Marginal cost per pound of payload | = 0.081 | Marginal cost per pound of payload | = 0.047 |

Note: All values of performance characteristics are scaled down by a factor of 100.

With these figures, the cost of producing aircraft with 1955-1961 performance characteristics, utilizing 1951-1954 technology, can be calculated. The average cost of 12.175 pounds of payload carried at 5.107 knots is 12.175x0.075, which equals 0.913. The cost, in the early time period, of carrying this payload at 7.906 knots equals 0.531x2.80 (7.91-5.11), or 1.484. The sum of these two figures, 2.397, represents the average cost, in the early period, of carrying 12.175 pounds of payload at 7.906 knots. In the same manner

the average cost of flying 7.906 knots while carrying 12.175 pounds of payload, can be calculated. The result equals 1.288. The large difference between these two figures indicates that this is a crude method of calculating average cost figures; however, it is, nevertheless, encouraging to note that both figures are greater than the mean value of the cost, for the later time period, of an aircraft with these same mean value performance characteristics.

This statistical analysis indicates that the cost estimating relationships developed are acceptable for use and can be applied to the problem addressed in this paper.

## VI. APPLICATION OF THE COST ESTIMATING RELATIONSHIP

Having successfully developed an applicable and creditable cost estimating relationship, it can now be used to calculate a quality change index. With this index, it is possible to apply the theory of hedonic price indexes to the study of the effect of technological change on United States Navy fighter aircraft flyaway cost and performance characteristics.

The quality change index as it applies to this study can take either of two equally acceptable forms. The first is the form described in Section III:

$$QCI = \hat{P}_t/\hat{P}_0 \quad ,$$

where QCI = quality change index, $\hat{P}_t = f_t(X_{1t},X_{2t})$, and $\hat{P}_0 = f_t(X_{10},X_{20})$. The second form is the same as Griliches [Ref. 7] used. It is as follows:

$$QCI = \hat{P}_t/\hat{P}_0 \quad ,$$

where $\hat{P}_t = f_0(X_{1t},X_{2t})$, and $\hat{P}_0 = f_0(X_{10},X_{20})$.

$\hat{P}_t$ and $\hat{P}_0$, in both alternative forms, are cost estimating relationships using appropriate sets of performance characteristics as inputs. The alternative forms simply provide the analyst a choice of time periods on which to base the calculation of the quality change index. This index, therefore, measures technological change as a ratio of the same

cost estimating relationships using two different sets of performance characteristics.

The next requirement for application of hedonic price index theory is an index designed to measure, exclusively, price change. Generally, this index will take the form, $P_t/P_0$. Again using the cost estimating relationships, an apparent price index is developed which takes the form:

$$API = \hat{P}_t/\hat{P}_0$$

where $\hat{P}_t = f_t(X_{1t},X_{2t})$ and $\hat{P}_0 = f_0(X_{10},X_{20})$.

Finally, a true price index is formed to measure "real" change in prices. This is accomplished by adjusting the apparent price index by the quality change index. The true price index, therefore, is formed as follows:

$$TPI = \frac{API}{QCI} = \frac{f_t(X_{1t},X_{2t})}{f_0(X_{10},X_{20})} \bigg/ \frac{f_t(X_{1t},X_{2t})}{f_t(X_{10},X_{20})}$$

$$TPI = \frac{f_t(X_{10},X_{20})}{f_0(X_{10},X_{20})}$$

for the alternate quality change index,

$$TPI = \frac{API}{QCI} = \frac{f_t(X_{1t},X_{2t})}{f_0(X_{10},X_{20})} \bigg/ \frac{f_t(X_{1t},X_{2t})}{f_0(X_{1t},X_{2t})}$$

$$TPI = \frac{f_t(X_{1t},X_{2t})}{f_0(X_{1t},X_{2t})}$$

The results of using the alternate forms of the quality change index are true price indexes which differ only in the set of performance characteristics used as inputs. This result is useful for comparison purposes. An example of the numerical calculation of each index is presented in Table Four.

In this paper, three approaches are taken in the numerical development of these indexes. For the true price index, the first approach is to use eight sets of actual performance data, one for each aircraft in the particular time period, calculate the true price index for each aircraft, then average the results over all eight aircraft. The second approach is to calculate the indexes directly using the mean values of the performance characteristic variables. The third approach is the same as the second except that median values are used in the calculations. Although it is not reasonable to form a set of quality change indexes which compare results obtained from calculations using the same regression equation with performance characteristics of two unrelated aircraft models as inputs, the indexes formed using mean and median characteristics are meaningful. Table Five shows the calculations for the three true price indexes and the two quality change indexes.

The collection of values for the quality change index vary over a range of 2.40 to 3.65. The choice of which regression equation to use in calculating the index does not

TABLE FOUR

EXAMPLE CALCULATIONS

$$\text{QCI} = \frac{\text{Average fighter of time 1 in regression equation for time 1}}{\text{Average fighter of time 0 in regression equation for time 1}}$$

$$\text{QCI} = \frac{-1.134 + 0.226(7.91) + 0.037(12.17)}{-1.134 + 0.226(5.11) + 0.037(\ 8.67)} = \frac{1.106}{0.343} = 3.225$$

$$\text{API} = \frac{\text{Average fighter of time 1 in regression equation for time 1}}{\text{Average fighter of time 0 in regression equation for time 0}}$$

$$\text{API} = \frac{1.106}{0.667} = 1.657$$

$$\text{TPI} = \frac{\text{API}}{\text{QCI}} = \frac{\text{Avg. fighter time 0 in regression eqn. for time 1}}{\text{Avg. fighter time 0 in regression eqn. for time 0}}$$

$$\text{TPI} = \frac{-1.134 + 0.226(5.11) + 0.037(8.67)}{-2.746 + 0.531(5.11) + 0.081(8.67)}$$

$$\text{TPI} = \frac{0.343}{0.667} = 0.514$$

## TABLE FIVE

## QUALITY CHANGE AND TRUE PRICE INDEX NUMERICAL VALUES

$$QCI = \frac{\text{fighter 1 in eqn. 1}}{\text{fighter 0 in eqn. 1}}$$

Mean QCI = 3.22

Median QCI = 2.40

$$QCI = \frac{\text{fighter 1 in eqn. 0}}{\text{fighter 0 in eqn. 0}}$$

Mean QCI = 3.65

Median QCI = 2.90

$$TPI = \frac{\text{fighter 0 in eqn. 1}}{\text{fighter 0 in eqn. 0}}$$

| Model | TPI |
|---|---|
| 1. | = 0.73 |
| 2. | = 0.57 |
| 3. | = 0.68 |
| 4. | = 0.54 |
| 5. | = 0.48 |
| 6. | = 0.49 |
| 7. | = 0.50 |
| 8. | = 0.63 |
| | 4.62/8.0 |

Average TPI = 0.58

Mean TPI = 0.51

Median TPI = 0.59

$$TPI = \frac{\text{fighter 1 in eqn. 1}}{\text{fighter 1 in eqn. 0}}$$

| Model | TPI |
|---|---|
| 1. | = 0.47 |
| 2. | = 0.50 |
| 3. | = 0.54 |
| 4. | = 0.65 |
| 5. | = 0.34 |
| 6. | = 0.43 |
| 7. | = 0.44 |
| 8. | = 0.44 |
| | 3.81/8.0 |

Average TPI = 0.48

Mean TPI = 0.45

Median TPI = 0.49

appear to be significant. Interpretation of the results indicates a roughly three fold increase in quality for the time period investigated.

Because of the magnitude of these indexes, another set was calculated, as a check, using the logarithmic form of the estimating relationship as shown in Appendix A. The result for the first method, 2.36, was comparable. The result for the second method, 12.82, gave further indication that, in part because of the large coefficient of mission speed, the logarithmic form should not be used.

The apparent price index indicates a sixty-six percent increase in the flyaway cost of the fighter aircraft between the two time periods covered by each model. Taking the median year of each period results in a time span of roughly 1953 to 1958 for this sixty-six percent change.

The range of the true price index values is 0.45 to 0.59. Although the values obtained using the set of performance characteristics for earlier models of fighter aircraft are generally greater than the values associated with later models, the difference is not large. The true price index, which measures price change adjusted for quality change, shows a decrease by a factor of approximately one-half.

The important implications of these results are discussed in the next section.

# VII. SUMMARY

Planning and programming decisions in the Department of Defense today are directed towards maximizing effectiveness with limited resources. Since changes in technology can have significant effects on this goal, a better understanding of technological change could be of considerable benefit to the decision maker.

In order to understand the effects of technological change, the analyst must be able to measure them. This paper has developed a performance cost estimating relationship which when used in conjunction with hedonic price index theory, measures technological change in the form of a quality change index. This index is then used to adjust an index of observed price changes, the result of which is a true price index.

The concept of measuring the effects of technological change is tested by applying the associated theory to the analysis of price change in Navy fighter aircraft procured over a period of 1951 to 1961. While it is obvious that procurement costs have increased significantly, the results of the analysis show that the increase in quality has also been significant. The true price index value of approximately 0.5, reveals that the apparent price change, adjusted for quality change in the performance characteristics, mission speed and payload, has actually decreased by roughly one-half.

These results together with the observed decrease in the marginal costs and in the average cost relationships, indicate that new technology gives improved performance characteristics at lower costs than old technology.

The substantial increase in aircraft unit cost has raised in the minds of many defense critics the question of whether it would not have been better to continue to buy older, cheaper aircraft. The analysis of this paper shows that if fighter aircraft are purchased for speed and payload, the introduction of new aircraft has enabled the Navy to buy more of these characteristics for any given budget.

APPENDIX A

LOGARITHMIC MODEL:

$$P = a_0 \begin{bmatrix} \text{mission} \\ \text{speed} \end{bmatrix}^{a_1} \begin{bmatrix} \text{mission} \\ \text{payload} \end{bmatrix}^{a_2}$$

$$\text{Log}_{10} P = \text{Log}_{10} a_0 + a_1 \text{Log}_{10} \begin{bmatrix} \text{mission} \\ \text{speed} \end{bmatrix} + a_2 \text{Log}_{10} \begin{bmatrix} \text{mission} \\ \text{payload} \end{bmatrix}$$

Statistics:

Time Period 1951-1954 Model

$$\text{Log}_{10} P = -4.606 + 4.946 \text{Log}_{10}[V_1] + 0.943 \text{Log}_{10}[V_2]$$

$R^2$ = 0.9305

SE = 0.09512

F =33.4576

"t"$_{a_1}$ = 4.10181

"t"$_{a_2}$ = 5.63356

Time Period 1955-1961 Model

$$\text{Log}_{10} P = -1.872 + 1.638 \text{Log}_{10}[V_1] + 0.381 \text{Log}_{10}[V_2]$$

$R^2$ = 0.8961

SE = 0.10784

F =21.5714

"t"$_{a_1}$ = 6.15743

"t"$_{a_2}$ = 1.10925

$$QCI = \frac{\text{fighter 1 in eqn. 1}}{\text{fighter 0 in eqn. 1}} = 2.36 \qquad QCI = \frac{\text{fighter 1 in eqn. 0}}{\text{fighter 0 in eqn. 0}} = 12.82$$

APPENDIX B

| AIRCRAFT MODEL | | COST (MILL$) | PREDICTED COST (MILL $) | SPEED (x 100 KNOTS) | PAYLOAD (x 100 POUNDS) | MISSION TIME (HOURS) |
|---|---|---|---|---|---|---|
| 1951-1954 Cost = -2.746 + 0.531(SPEED) + 0.081(PAYLOAD): | | | | | | |
| 1951 | F9F 5 | 0.274 | 0.15646 | 4.75 | 4.71 | 2.35 |
| 1952 | 6 | 0.288 | 0.32275 | 5.13 | 4.27 | 1.69 |
| 1952 | 7 | 0.265 | 0.17937 | 4.86 | 4.27 | 2.12 |
| 1953 | 8 | 0.332 | 0.55054 | 4.55 | 10.91 | 2.06 |
| 1954 | F3H2N | 1.580 | 1.47710 | 5.26 | 17.72 | 1.88 |
| 1954 | F4D1 | 0.757 | 0.72409 | 5.65 | 8.30 | 1.70 |
| 1954 | FJ4 | 0.774 | 0.85237 | 5.36 | 9.32 | 2.30 |
| 1954 | FJ4B | 1.060 | 0.86733 | 5.30 | 13.00 | 2.00 |
| | MEAN | 0.666 | | 5.11 | 8.67 | 2.01 |
| | MEDIAN | | | 5.20 | 8.81 | |
| 1955-1961 Cost = -1.134 + 0.226(SPEED) + 0.038(PAYLOAD): | | | | | | |
| 1955 | F11F1 | 0.803 | 0.58182 | 6.08 | 9.20 | 1.57 |
| 1956 | FJ4B | 0.534 | 0.43160 | 5.30 | 9.90 | 2.00 |
| 1956 | F9F8 | 0.303 | 0.29969 | 4.55 | 10.91 | 2.06 |
| 1956 | F3H2 | 0.953 | 0.99499 | 6.21 | 19.52 | 2.06 |
| 1956 | F8U1 | 0.945 | 1.32363 | 8.50 | 12.62 | 1.90 |
| 1957 | F8U2 | 1.100 | 1.38242 | 9.81 | 9.83 | 1.81 |
| 1958 | F8U2N/2NE | 1.590 | 1.44810 | 9.81 | 9.83 | 1.81 |
| 1961 | F4A/B | 2.610 | 2.37877 | 12.90 | 16.08 | 1.71 |
| | MEAN | 1.11 | | 7.91 | 12.17 | 1.84 |
| | MEDIAN | | | 7.50 | 10.40 | |

# APPENDIX C

## SUMMARY OF STATISTICS

Time Period 1951-1954 Model

$P = -2.746+0.531X_1+0.081X_2+u$

$X_1$ = Mission Speed

$X_2$ = Mission Payload

$R^2 = 0.9038$

$SE = 0.1744$

$CV = 0.262$

$F = 22.4808$

$\overline{P} = 0.666$

| $X_1$ Statistics | $X_2$ Statistics |
|---|---|
| $S_{a1} = 0.18726$ | $S_{a2} = 0.01499$ |
| "$t_1$" = 2.83586 | "$t_2$" = 5.38235 |
| $\overline{X}_1 = 5.107$ | $\overline{X}_2 = 8.675$ |

Correlation Coefficients

| | Flyaway Cost | Mission Speed | Mission Payload |
|---|---|---|---|
| Flyaway Cost | 1.0000 | 0.2385 | 0.5884 |
| Mission Speed | | 1.0000 | 0.8655 |
| Mission Payload | | | 1.0000 |

Time Period 1955-1961 Model

$P = -1.134+0.226X_1+0.047X_2+u$

$X_1$ = Mission Speed

$X_2$ = Mission Payload

$R^2 = 0.9014$

$SE = 0.2667$

$CV = 0.263$

$F = 22.8039$

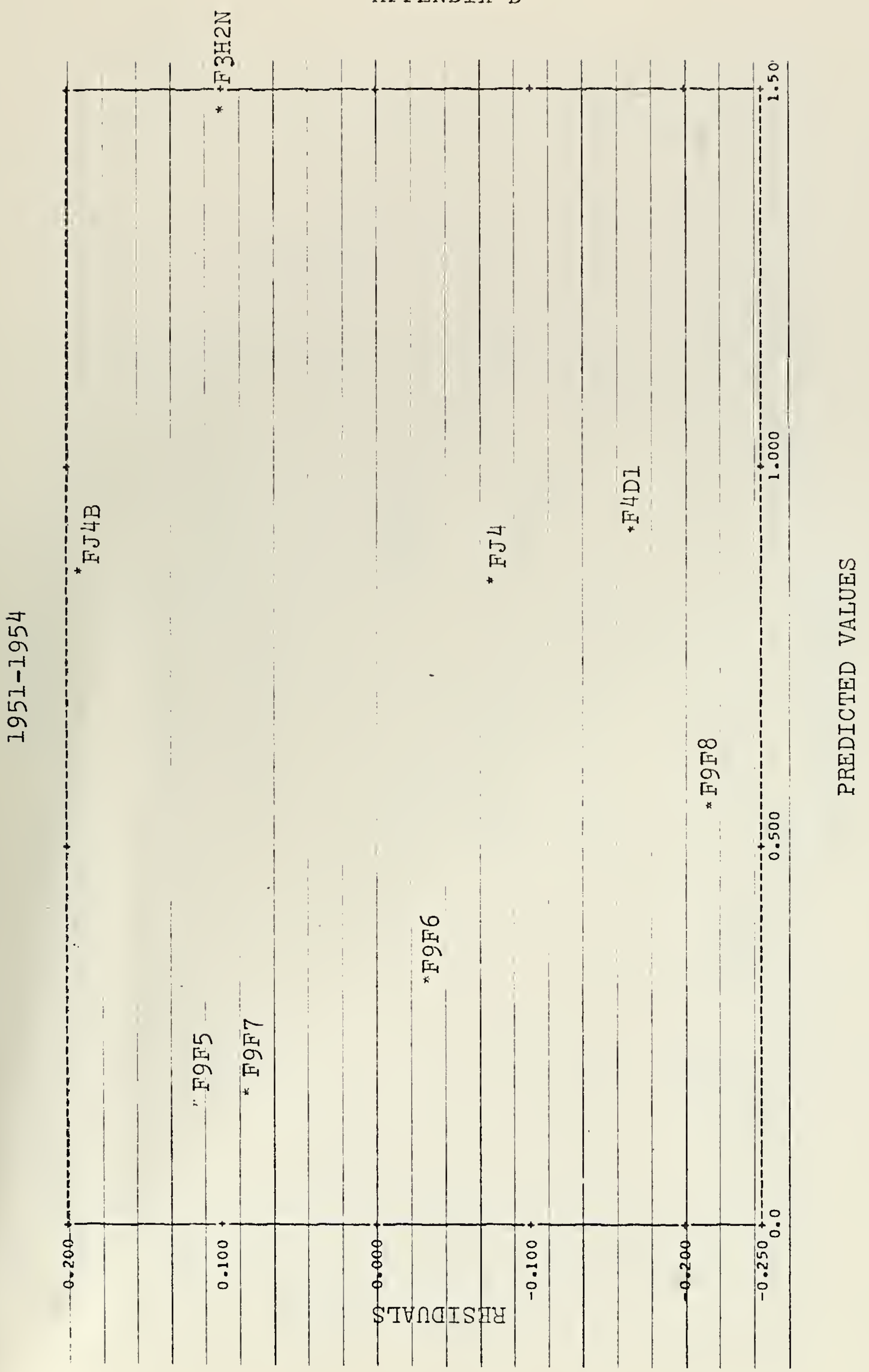
$\overline{P} = 1.105$

| $X_1$ Statistics | $X_2$ Statistics |
|---|---|
| $S_{a1} = 0.03610$ | $S_{a2} = 0.02734$ |
| "$t_1$" = 6.25875 | "$t_2$" = 1.36050 |
| $\overline{X}_1 = 7.906$ | $\overline{X}_2 = 12.175$ |

Correlation Coefficients

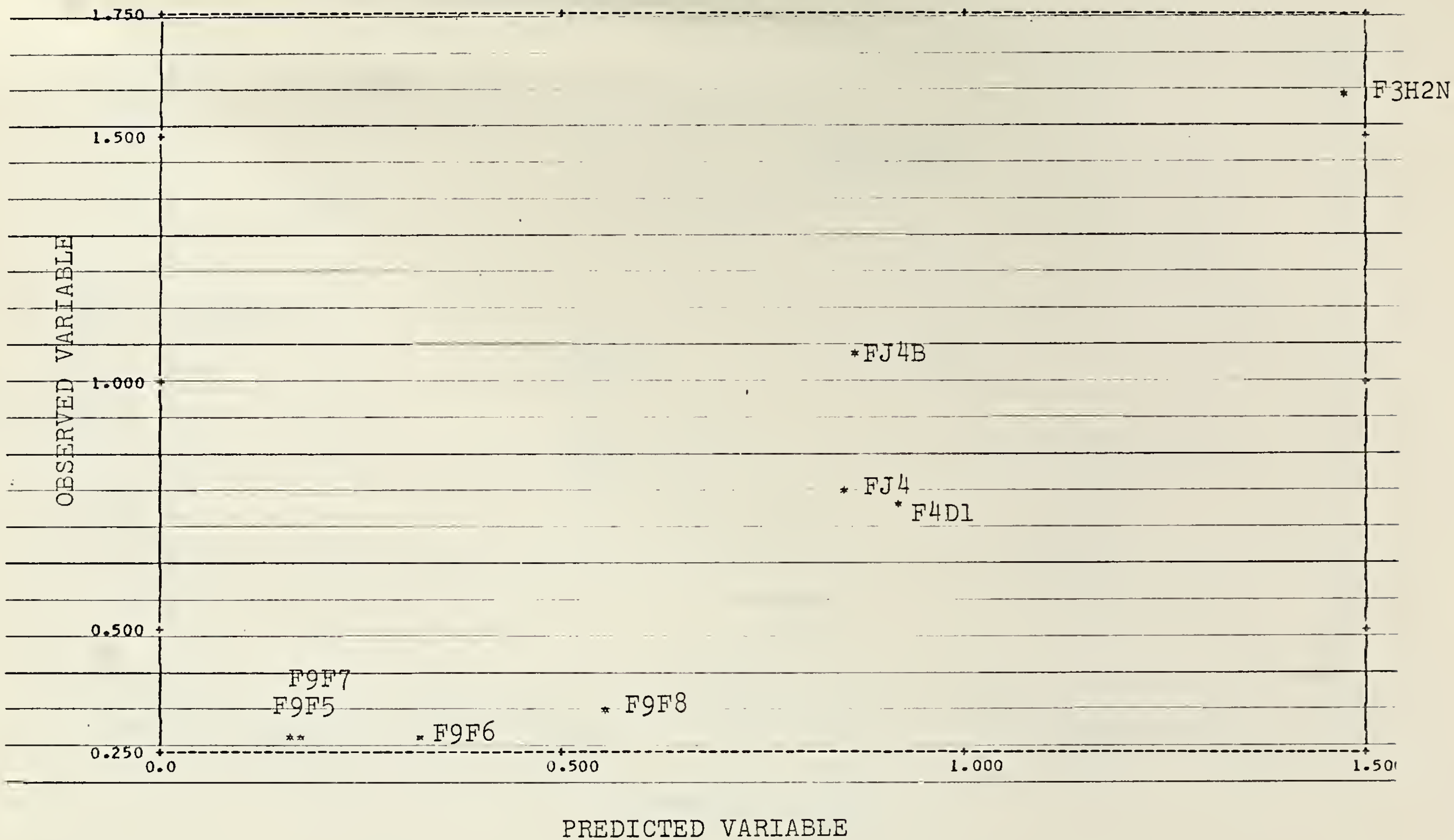
| | Flyaway Cost | Mission Speed | Mission Payload |
|---|---|---|---|
| Flyaway Cost | 1.0000 | 0.1847 | 0.9300 |
| Mission Speed | | 1.0000 | 0.3595 |
| Mission Payload | | | 1.0000 |

APPENDIX D



1951-1954
RESIDUALS
PREDICTED VALUES
0.200
0.100
0.000
-0.100
-0.200
-0.250
0.0
0.500
1.000
1.50
F3H2N
FJ4B
FJ4
F4D1
F9F8
F9F6
F9F5
F9F7

1951-1954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1.500
1.000
0.500
0.250
OBSERVED VARIABLE
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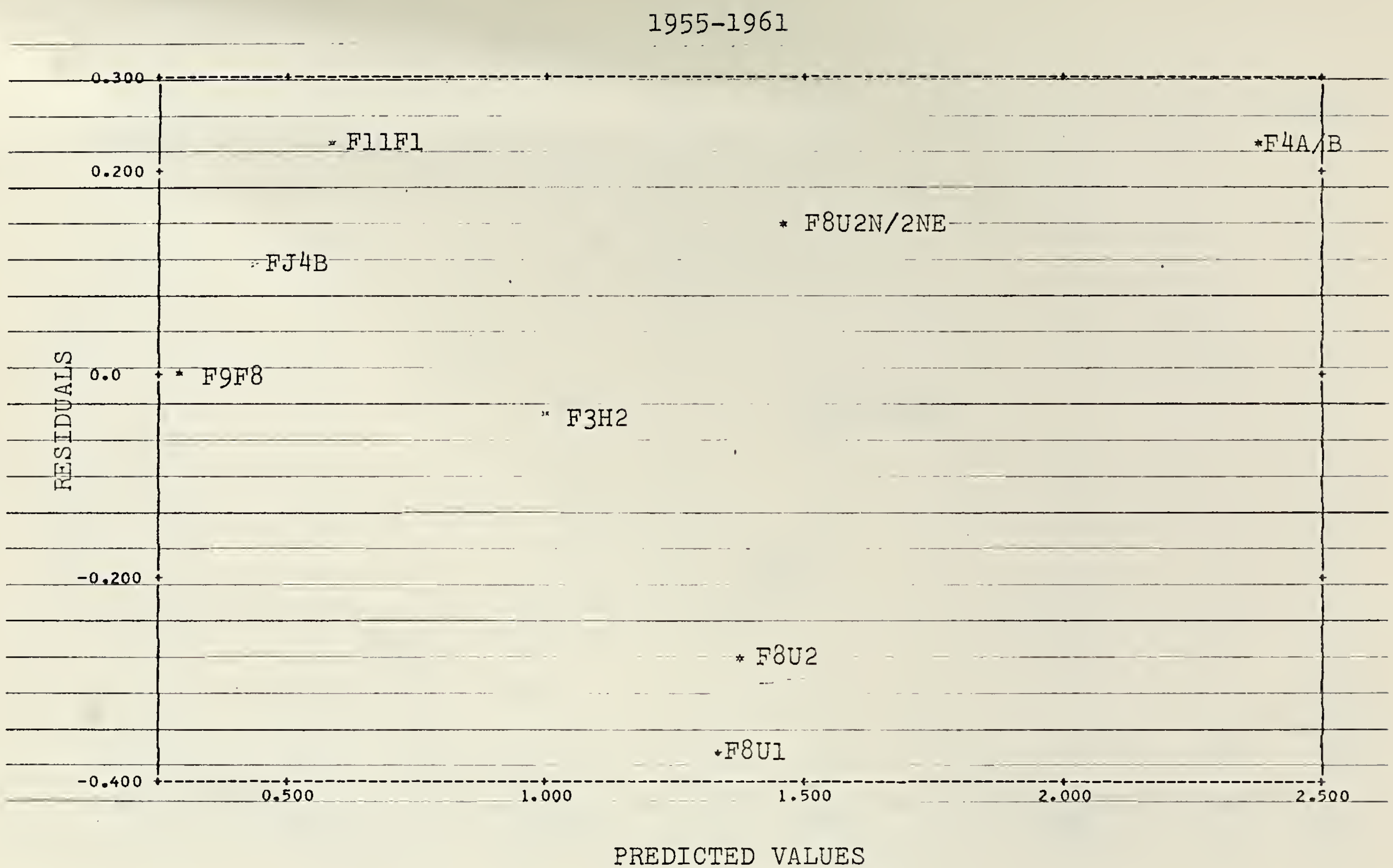
0.500
1.000
1.500
F3H2N
FJ4B
FJ4
F4D1
F9F7
F9F5
F9F8
F9F6
PREDICTED VARIABLE



1955-1961
0.300
0.200
0.0
-0.200
-0.400
RESIDUALS
F11F1
F4A/B
F8U2N/2NE
FJ4B
F9F8
F3H2
F8U2
F8U1
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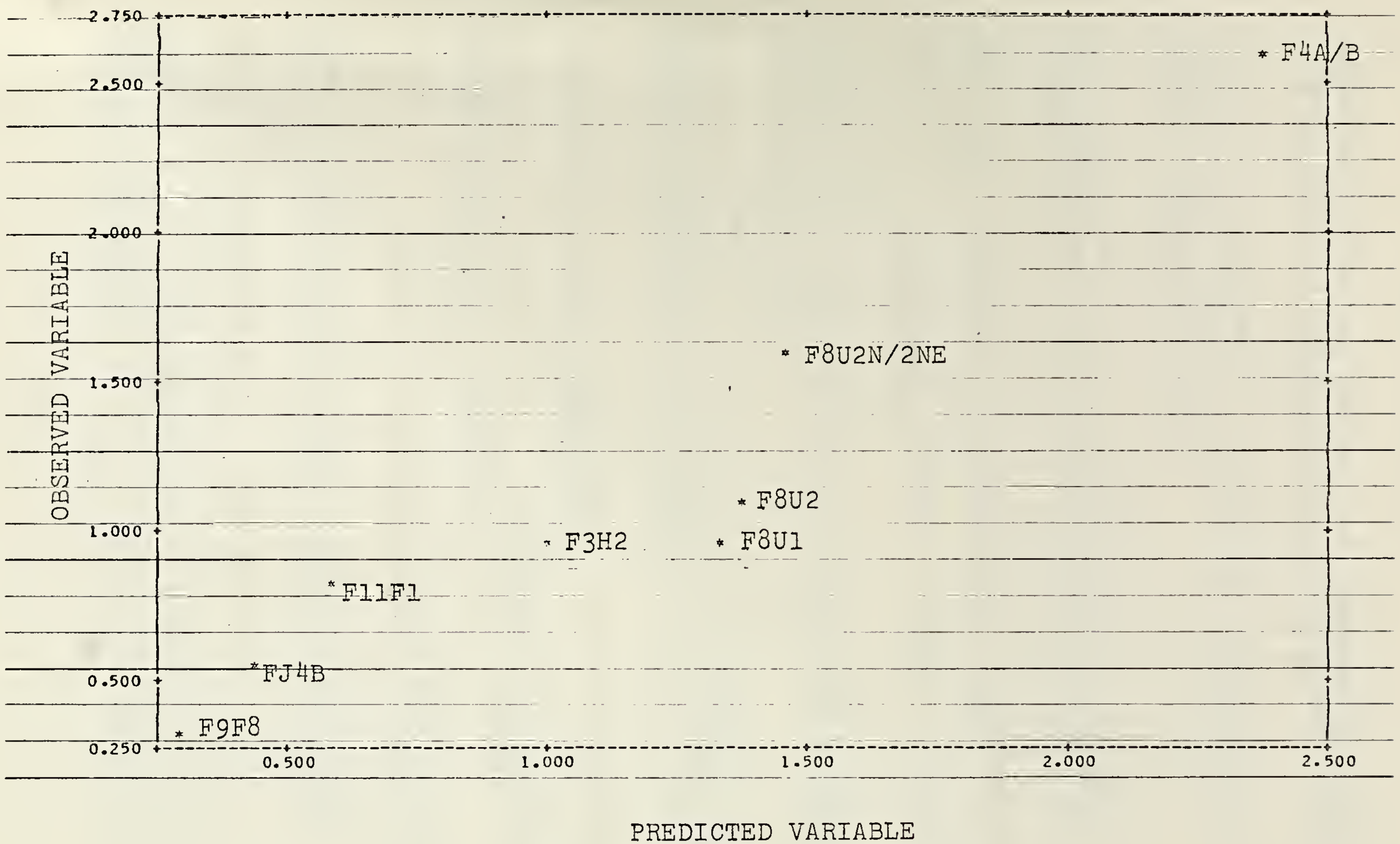
1.000
1.500
2.000
2.500
PREDICTED VALUES

1955-1961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2.500
2.000
1.500
1.000
0.500
0.250
F4A/B
F8U2N/2NE
F8U2
F3H2
F8U1
F11F1
FJ4B
F9F8
0.500
1.000
1.500
2.000
2.500
PREDICTED VARIABLE

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The purpose of this study was to develop a performance cost estimating relationship which when used in conjunction with hedonic price index theory, measures technological change in the form of a quality change index. This index was applied to the analysis of price change in Navy fighter aircraft, procured over a period of 1951 to 1961, by adjusting an index of observed price changes to yield a true price index. The resulting analysis

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showed that if fighter aircraft are purchased for speed and payload, the introduction of new aircraft has enabled the Navy to buy more of these characteristics for any given budget.

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